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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MBA PROFESSIONAL REPORT

INVENTORY MANAGEMENT OF CHOLERA VACCINATIONS IN THE EVENT OF COMPLEX NATURAL DISASTERS

December 2015

By: Joshua A. Gregory
Christine Taranto

Advisors: Aruna Apte
Bryan Hudgens

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INVENTORY MANAGEMENT OF CHOLERA VACCINATIONS IN THE EVENT OF COMPLEX NATURAL DISASTERS

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Submitted in partial fulfillment of the requirements for the degree of

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from the

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INVENTORY MANAGEMENT OF CHOLERA VACCINATIONS IN THE EVENT OF COMPLEX NATURAL DISASTERS

ABSTRACT

This MBA Project explores the considerations and recommendations for mass vaccination campaigns in response to natural disasters and their secondary effects, specifically cholera epidemics and the vaccine stockpile necessary to effectively treat the disease. Cholera is a significant post-disaster risk to an already affected population. As a first responder to these disasters, the Marine Air Ground Task Force (MAGTF) must consider an epidemic cholera outbreak as a threat to mitigate and be considered in the planning process for Humanitarian Aid/Disaster Relief (HA/DR) scenarios. This project considers these factors based on former HA/DR events as well as an inventory management model that determines optimized stock pile of vaccinations necessary in a given year in order to reduce the number of lives lost to cholera.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADD	Acute Diarrheal Disease
ARG	Amphibious Ready Group
CDC	Center for Disease Control
CFR	Case Fatality Rate
CRED	Centre for Research on the Epidemiology of Disasters
CVIM	Cholera Vaccine Inventory Model
EF-21	Expeditionary Force-21
EM-DAT	Emergency Events Database
FEMA	Federal Emergency Management Agency
GFR	Global Response Force
GOB	Government of Bangladesh
HA	Humanitarian Assistance
HA/DR	Humanitarian Assistance/Disaster Relief
HAST	Humanitarian Aid Survey Team
HSS	Health Service Support
HSSD	Health Service Support Detachment
ICG	International Coordinating Group
IFRC	International Federation of Red Cross
MAGTF	Marine Air Ground Task Force
MCPP-N	Marine Corps Prepositioning Program-Norway
MEDLOG	Medical Logistics Company

MEU	Marine Expeditionary Unit
MPF	Maritime Prepositioning Force
MSPP	Ministry of Public Health and Population
NDCSM	Natural Disaster and Cholera Simulation Model
NGO	Non-Government Organizations
OASD	Office of the Assistant Secretary of Defense
OCV	Oral Cholera Vaccine
ONR	Office of Naval Research
OTW	Other Than War
ROMO	Range of Military Operations
USAID	United States Agency for International Development
USMC	United States Marine Corps
VSL	Value of Statistical Life
WASH	Water, Sanitation, and Hygiene
WC	Whole-Cell
WHA	World Health Assembly
WHO	World Health Organization

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I. INTRODUCTION

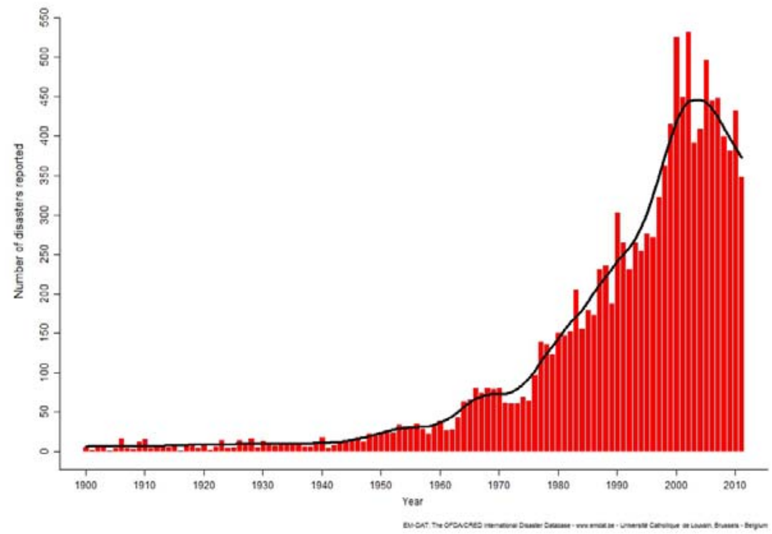
A. BACKGROUND

Natural disasters have the ability to change the course of history. Whether it is a 2004 tsunami in Southeast Asia or a 2010 earthquake in Haiti, these events mobilize a global response in a short time in order to assist the local government in saving lives. While the logistics associated with humanitarian assistance and disaster relief (HA/DR) are extremely difficult, given the short time window, planners often overlook the second- and third-order effects after a disaster which have the potential to endanger hundreds if not thousands of lives if not properly planned for.

While the occurrence of reported natural has followed a downward trend in recent years (Figure 1), the percentage of the global population that is affected by natural disasters is still rising (Figure 2). Countries, their governments, the United Nations, and Non-Government Organizations (NGOs) will be strained to provide adequate humanitarian aid and support to reduce human suffering on a global scale.

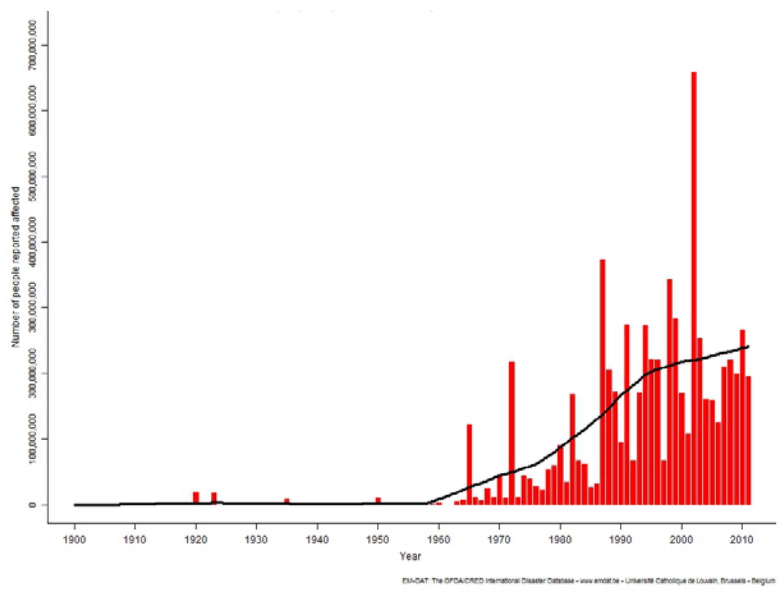
Humanitarian aid is a combination of disaster response and humanitarian relief. Disaster response hinges on limited information about the demand of critical supplies required to support the affected population and tends to be “reactionary logistics” (Apte, 2009). Humanitarian relief is the “ongoing process for slow-onset disasters with a long-term need for supplies” (Apte, 2009, p. 16). The affected population includes those who have become refugees or displaced persons as a result of some complex emergency or disaster whether man-made or natural. The primary purpose of humanitarian aid is to reduce suffering and save lives. As Kopinak (2013) states, “Humanitarian aid represents a commitment to support vulnerable host populations that have experienced a sudden emergency, requiring ongoing assistance to maintain or improve their quality of life.”

Figure 1. Natural disasters reported 1900–2011



Source: Center for Research on the Epidemiology of Disasters (CRED), n.d.

Figure 2. Number of people reported affected by natural disasters 1900–2011



Source: Center for Research on the Epidemiology of Disasters (CRED), n.d.

The use of the United States Military in HA/DR operations is not a new concept. In fact, "the United States is the most proactive country in the world for making its military assets available for disaster response" due to its extensive number of bases

worldwide, strategically positioned ships, and disposal of supporting financial resources (Wiharta, 2008, p. 12). HA/DR operations are pivotal means combatant commanders utilize aid to shape and influence the socioeconomic and geopolitical factors, infrastructure and U.S. military perception in affected nations within their area of operations (Office of the Assistant Secretary of Defense [OASD], 2011). Research students Gastrock and Iturriaga (2013, p. 2) summarize the Office of Naval Research [ONR] (2008), that "the *Marine Corps Vision and Strategy of 2025* lists preventing and responding to disasters in the top five priorities under the National Strategic Planning Guidance."

As the Department of Defense expands its missions beyond direct combat, HA/DR operations have become one of the most significant missions executed by the United States Navy and United States Marine Corps (Greenfield & Ingram, 2011, p. 4). From 2000–present the United States Military has deployed to provide substantial aid with significant frequency for HADR operations. Over the past decade, the Navy/Marine Corps team has responded to relief efforts both within the continental United States and around the world. According to OASD (2011), "although these events are sporadic and relatively low in frequency, their severity creates a demand for assistance that is most readily supplied by the U.S. military" (Gastrock & Iturriaga, 2013). The U.S. disaster assitance has proveded much needed manpower and supplies to aid in the relief of human suffereing for populations affected by disaters (Greenfield & Ingram, 2011).

One of the military services, The United States Marine Corps (USMC), develops its force organization based upon a flexible Marine Air Ground Task Force (MAGTF) that serves as the primary organization of forces for missions across the Range Of Military Operations (Expeditionary Force-21 [EF-21], 2014). The USMC utilizes the Marine Expeditionary Unit (MEU) as a Global Response Force (GRF) to provide an immediate response to crisis across the globe. Military prepositioned assets in strategic regions can be utilized and exploited by the USMC MEU in order to provide sustained MAGTF response in a succinct and timely manner (EF-21, 2014). These prepositioned assets include use of the Maritime Prepositioning Force (MPF) and Marine Corps Prepositioning Program-Norway (MCPP-N). With the increasing number of USMC

responses to conduct HA/DR operations, the USMC needs to evaluate its own capabilities. The capability we focus on in this project is to provide preventative medicine care during these natural disasters to help combat the spread of epidemics, one of the results of the primary disaster due poor sanitary conditions and to instability of infrastructure, economy, and at times poor socioeconomics.

Endemic and epidemic-prone cholera increases in transmission after natural disasters due to increased contamination of drinking water, austere and unsanitary living conditions, and the malnutrition resulting from lack of food, according to the World Health Organization (WHO) (2006a). As a result, WHO reported that over 470,000 cases of cholera were detected in the 2010 Haiti earthquake alone with over 6,500 deaths associated with the disease (WHO, 2010a). Since cholera most often occurs in developing countries where water and wastewater mix, the post-natural disaster environment is a breeding ground for this disease. Between 2004 and 2013, The World Disaster Report (2014) states there were 2,021 earthquake or flood disasters, each with the potential to infect hundreds of thousands of people. These disasters and their associated outbreaks have begun to gain global attention. Such attention will improve epidemic cholera preparedness and response measures as well as the importance of preventative actions to reduce the inevitable outbreaks in endemic areas.

As of July 2014, the WHO has stated a need for an oral cholera vaccine (OCV) stockpile with at least two million doses of the vaccine to be managed by The International Coordinating Group (ICG), which is already responsible for managing vaccine inventories such as meningococcal meningitis and yellow fever. "The ICG members will continue to communicate with partners and stakeholders to increase awareness of the OCV stockpile, placing vaccine in the context of an integrated cholera response which is based around early detection, case management, provision of safe water, sanitation, and raising awareness among the affected communities" (WHO, n.d.)

The ICG (2013) summarizes that the main objective of the OCV stockpile is to:

> Ensure the timely and targeted deployment of OCV such that vaccines can be used as an effective outbreak response where it is most needed. The main use of this stockpile will be for outbreak response, either in the form

> of reactive campaigns in areas experiencing an active outbreak or pre-emptive vaccination campaigns among populations at elevated risk for cholera due to outbreaks in adjacent areas or at heightened vulnerability due to humanitarian crisis. (pp. 16–17)

Vaccines will be used for emergency response situations and provide a short-term intervention effect against potential cholera outbreaks while populations affected by disasters are most at-risk. Long-term solutions for cholera and other waterborne diseases must be focused on access to improved sanitation conditions and purified water sources (ICG, 2013).

B. OBJECTIVE

The goal of any HA/DR operation is to reduce casualties and human suffering of the affected population. Our focus is to mitigate the spread of secondary disasters, such as a cholera epidemic, using optimal inventory levels of vaccines and timing of dispensing at early onset with the United States Marine Corps (USMC), specifically Marine Expeditionary Units, as a distribution channel.

C. METHODOLOGY

This research uses optimization and simulation as methodology. We developed a "newsvendor" or "newsboy" inventory model to optimize the number of vaccinations based on the average net penalties created by having too many or too few doses of vaccines within a stockpile for a given year, given the demand distribution. The newsvendor model is a useful tool to establish an optimized order quantity for perishable items (i.e., vaccines) that will maximize profit, given there is a known demand distribution. The single period model "assumes that if any inventory remains at the end of the period, a discount is used to sell it or it is disposed of" (Nahamias, 1996). If demand exceeds supply during the period, the firm or seller will lose potential profits (Khouja, 1999).

Since the occurrence of natural disasters and their secondary epidemic cholera outbreaks are stochastic, we utilized the program Crystal Ball to simulate the probability of natural disasters occurring multiple times within one year. As Balakrishnan, Render,

and Stair (2013, p. 408) state, “To simulate is to try to duplicate the features, appearance, and characteristics of a real system.” We simulated the probability of natural disasters occurring by utilizing a mathematical model to replicate the impact of cholera without any real world ramification.

We utilized the simulation program Crystal Ball because it offers the following features over other simulation programs:

> 1. Built-in functions to simulate not only from the simple probability distributions discussed so far but also from many other distributions that are commonly encountered in practice (e.g., binomial, triangular, or lognormal). 2. Built-in procedures that make it very easy to replicate the simulation model several hundred (or even several thousand) times. 3. Built-in procedures that make it easy to collect and present information on various output measures. These measures can also be displayed graphically, if desired. (Balakrishnan et al., 2013, p. 414)

We based our research and analysis on the methodology discussed, literature reviewed, and data collected. The data was collected using public sources of information and based on the literature review. The literature review consists of a survey of academic journal articles, United States Agency for International Development (USAID) documents, USMC orders, directives, and standard operating procedures, and “after action reports” from both the USMC, USAID, and WHO. Our scope of review will focus on occurrence of past natural disasters, secondary cholera epidemics from natural disasters, existing pandemic cholera, and global supply prepositioning to support HA/DR operations on a global scale.

Data for analysis was collected in three separate categories.

1. Natural disaster data collected from the Emergency Events Database (EM-DAT), the WHO, and various NGOs with focus on natural disasters that had secondary cholera epidemics.

2. USMC medical response to HA/DR efforts with data collected from after action reports from MEUs and Medical Logistics Company (MEDLOG) with focus on distribution capabilities and shortfalls for managing a vaccine supply chain.

3. Data collected from the WHO and Center for Disease Control (CDC) on the preexisting OCV stockpile.

The report is organized as follows: Chapter II reviews literature relevant to our focus and describes our contribution in reference to it. Chapter III focuses on the development and use of simulation and optimization models for use in optimizing the national stockpile of OCV. Chapter IV offers our conclusion and recommendations for further research.

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II. LITERATURE REVIEW

In this chapter, we review literature to offer background for the topic. We also outline literature on the health impacts of disasters, specifically the outbreak of cholera in selected disasters such as, the 2005 earthquake in Pakistan, Super Cyclone Sidr in Bangladesh in 2007and the 2010 earthquake in Haiti. These descriptions offer an insight into the cause and devastation of secondary disaster of an outbreak. For the focus of our report this is the demand for vaccinations. On the supply side, we review literature about the stockpile of vaccines and process of disseminating in complex emergencies. A major supplier of relief for this need is the United States Marine Corps. We discuss how the Marine Expeditionary Unit helps in this respect based on Marine Corps doctrine and after action reports.

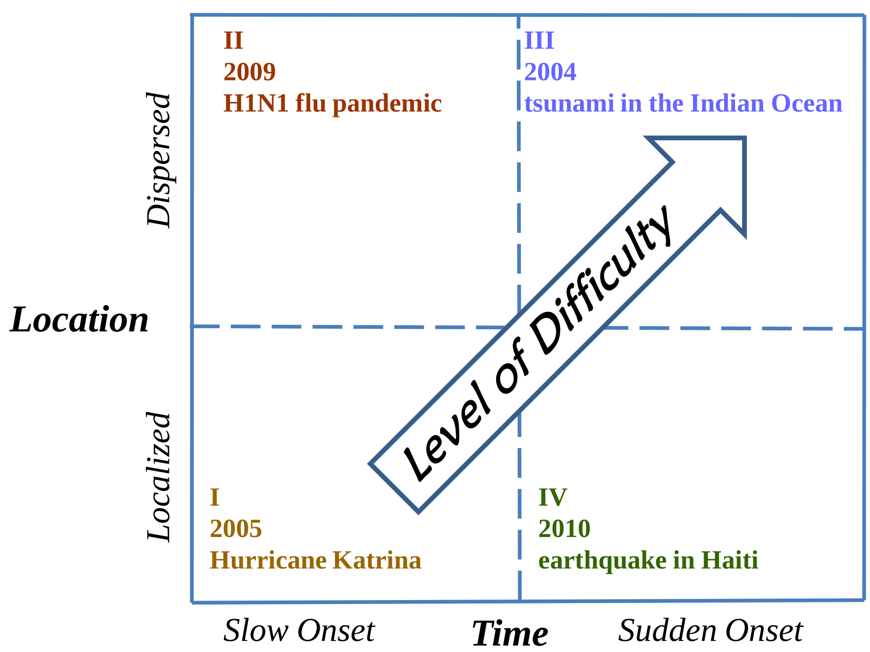
A. NATURAL DISASTERS

The Federal Emergency Management Agency (FEMA) is one the leading sources for disaster information within the United States. Greenfield and Ingram (2011, p. 9) summarize the FEMA (2010) definition of a natural disaster as an event that results "in a minimum of 100 deaths/injuries or result in over $1 million worth of damage." High impact or substantial damage must occur from the disaster in order for federal relief efforts to be authorized. Internationally, disasters are classified and analyzed by the Centre for Research on the Epidemiology of Disasters (CRED). CRED collects and centralizes disaster data into the Emergency Events Database (EM-DAT). In order to be included in the database, it must meet CRED's definition of a disaster. This includes at least one of the following criteria: "10 or more people killed, 100 or more people affected, declaration of a state of emergency, call for international assistance" (EM-DAT, 2011).

Former classifications of natural disasters were limited to either natural (earthquake, hurricane, cyclone) or manmade (genocide, civil disorder, war, terrorism) (Apte, 2009, p. 13). Disasters are now "classified based on the specific characteristics of disasters, including the speed of onset, slow or sudden; and the source, natural or

manmade" (Apte, 2009, p. 13). By expanding the disaster classfication system, emergency planners and responders can more realistically plan for the complexities associated with individual charactersictics of disasters vice a "one size fits all" solution (Apte, 2009, pp. 13–14). Disasters that are slow onset, but widespread are challenging to respond to because while preparation maybe adequate, prepositioning supplies becomes the challenge (Apte, 2009, p. 14). Disasters that are localized but strike without warning pose different challenges as humanitarians do not have time to prepare, but the localization is less operationally difficult than a dispersed disaster (Apte, 2009, p. 15). The degree of difficulty associated with the relief operations based on the category of disaster is displayed in Figure 3. Gastrock and Iturriaga (2013, p. 7) state: "response to any level of disaster must accomplish several capabilities to meet wide range of demand for HA/DR relief. These necessary response deliverables include information and knowledge management, needs assessment, supply, deployment and distribution, health service support, and collaboration/governance" (Apte, 2009).

Figure 3. Classification of disasters



Source: Apte, A., & Yoho, K. (2014). Strategies for logistics in case of natural disaster. *International Journal of Operations and Quantitative Management, 20*(4), 101–119.

“Natural disasters produce a range of impacts, which are often broadly classified as ‘direct’ and ‘indirect’ impacts” (Paul, Rahman, & Rakshit, 2011, p. 842). Paul et al. (2005, pp. 842-843) suggest “direct impacts are caused by physical contact of disaster with humans or property, whereas indirect impacts are caused by the ramifications of such physical contact during post-disaster period.” Indirect impacts or secondary disasters also referred to as “second web of death and at hazards destruction” have the ability to increase human suffering more than the direct impacts from the original natural disaster (Paul et al., 2011).

Tomasini and Wassenhove (2009) define humanitarian action into three principles widely accepted by the academic community as:

> Humanity, neutrality, and impartiality and all three must be present to constitute a humanitarian operation. Humanity implies that human suffering should be relieved wherever found and is the very reason why humanitarian organizations deploy. Neutrality implies relief should be provided without bias or affiliation to a party to avoid getting trapped by underlying political agendas. Impartiality indicates assistance should be provided without discrimination and with priority given to the most urgent needs. (pp. 20–21)

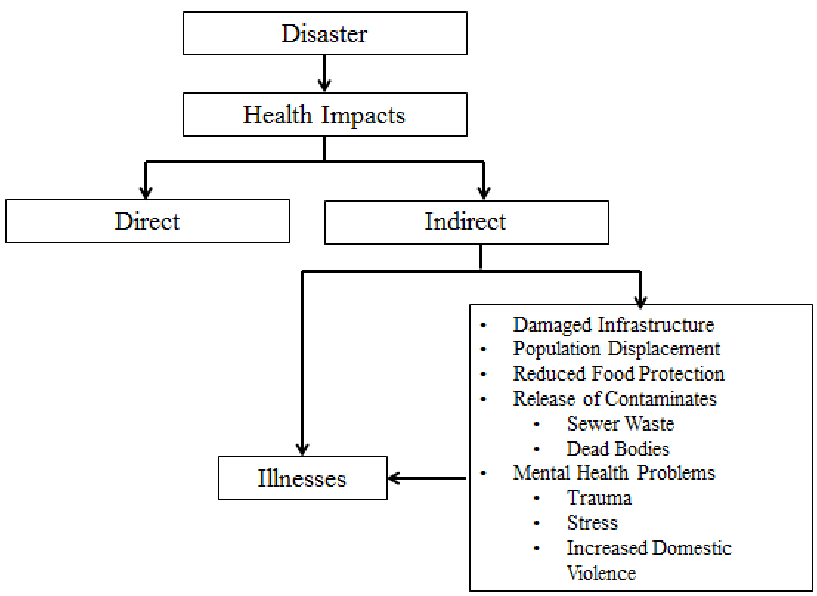
The most devastating effects from natural disasters include direct human suffering and death. Indirect health impacts can manifest as secondary disasters when outbreaks or epidemics of “communicable, water-related, and other diseases, such as diarrhea, hepatitis, malaria, fever, pneumonia, eye infections, and skin diseases” occur (Paul, et al., 2011, p.843). The severity of outbreak and disease transmission post disaster can be associated to the size of the population that has been displaced from primary residences and basic infrastructure. “Proximity of safe water and functioning latrines, the nutritional status of the displaced population, the level of immunity to vaccine-preventable diseases, and the access to healthcare services” will also determine the possibility of secondary disasters and outbreaks (Connolly, Gayer, & Watson, 2007, p. 1). “Disaster survivors generally live in damp, dirty, and cramped conditions in their homes or temporary shelters. Such [sic] conditions facilitate spread of numerous adverse health effects from person to person within the household” (Paul et al., 2011 p.843).

These adverse health effects are associated with increased illness and spreading of disease within a population which manifest readily with the "indirect impacts of extreme events such as damaged infrastructure, population displacement, reduced sanitary food production, and the release of contaminates into the water (e.g., from storage and waste disposal sites)" (Figure 4) (Haque et al., 2012, p. 151).

Paul, Rahman, and Rakshit (2011) state:

> In the context of health impacts, damaged infrastructure primarily refers to health care facilities such as hospitals, medical clinics, and ambulatory services, but also to the electricity on which most of these facilities depend. Because of either complete or partial damage to such facilities caused by natural disasters, it is difficult to provide necessary care to the ill and injured. Lack of proper medical attention may also result from the absence of physicians and/or an insufficient supply of appropriate medicine. These indirect impacts not only prolong suffering, it also increases [sic] the probability of death from injuries and/or illnesses. (p.843)

Figure 4. Indirect impacts causing illness



Source: Paul, B., Rahman, M., & Rakshit, B. (2011). Post-Cyclone Sidr illness patterns in coastal Bangladesh: An empirical study. *Natural hazards*, *56*(3), 841–852.

Cholera, whether epidemic or endemic, is one of the diseases that increase in transmission post natural disasters. This transmission is heightened in developing nations.

"An outbreak of diarrheal disease post flooding in Bangladesh in 2004 involved >17,000 cases, with the isolation of *Vibrio cholerae* (O1 Ogawa and O1 Inaba) and enterotoxigenic *Escherichia coli.* A large (>16,000 cases) cholera epidemic (O1 Ogawa) in West Bengal in 1998 was attributed to preceding floods, and floods in Mozambique in January–March 2000 led to an increase in the incidence of diarrhea" (Connolly et al., 2007, p.2).

The risk of a secondary disaster resulting in a cholera outbreak is negatively correlated to how developed the nation is. After the December 2004 Indonesian tsunami, health assessments conducted two weeks post disaster found that 85% of the affected population that continued to drink from unprotected wells, reported diarrhea within the same time period (Connolly et al., 2007, p. 2). Following the 2005 Pakistan earthquake, a cholera outbreak was reported within a makeshift displaced persons camp. "The outbreak involved over 750 cases, mostly adults, and was controlled following the provision of adequate water and sanitation facilities" (Connolly et al., 2007, p. 2).

B. PAKISTAN EARTHQUAKE

On October 8, 2005, a major earthquake registering 7.6 on the Richter scale struck northern Pakistan and Kashmir, killing 73,320, injuring 69,392, and displacing more than 2.5 million people from their homes (OCHA, 2005).

Post-quake, the living conditions quickly deteriorated for most the population. Huggler (2005) reported that "people are living crammed together, five families to a single tent. There just aren't enough tents to go around and not enough room in them ... The ground is covered with human feces and open sewers run through the refugee camps. There has been a serious diarrhea epidemic and, although aid workers will only whisper it, there are growing fears of a cholera outbreak." "In other words, if not cold and snowfall, then a dismal living environment and diseases posed such a great threat to the well-being of the disaster-affected people that the UN Secretary General, Kofi Annan, had to warn the world's public of the 'second massive wave of death'" (O¨Zerdem, 2006, p. 403).

While there were minimal reported cases of cholera after the earthquake, the lack of sanitation within the refugee camps resulted in 1,783 cases of acute diarrheal disease (ADD) between 14 October and 17 December 2005 in Tangdar (population 65000). Children under four years of age suffered 20% of the overall attack rate (Karmakar et al., 2008).

> Following the earthquake, drinking stream water or tap water without boiling or chlorination may have led to a common source water-borne outbreak of rotavirus gastroenteritis. Other contributing factors were: overcrowding; poor sanitation; open-air defecation; poor hygiene; and living in makeshift camps near streams. Person-to-person transmission may also have contributed to perpetuation of the outbreak. Once proper medical camps were established the education and the dissemination of information with respect to proper hygienic practices brought the outbreak under control. (Karmakar et al., 2008, p. 982).

Ultimately, a cholera epidemic did not occur because the earthquake occurred just before winter in a mountainous region of Pakistan. The extremely cold conditions were not favorable to growth and spread of *V. cholerae* (Jutla et al., 2013).

C. SUPER CYCLONE SIDR

In November 2007, Category IV storm Super Cyclone Sidr made landfall along the southwestern coast of Bangladesh. Deaths caused by Sidr were estimated at 3,406, with over 1,000 missing, and in excess of 55,000 people sustaining physical injuries (GOB, 2008a). Cyclone Sidr, had been one of the worst cyclones to hit the Bangladesh coast since 1991, and "given the severity of Cyclone Sidr, the projected destruction from the storm was expected to be much higher than what ultimately occurred" (GOB, 2008b). Paul (2009) notes "The relatively low number of deaths experienced with Sidr is widely considered the result of Bangladesh government's efforts to provide timely cyclone forecasting and early warnings, and successful evacuation of coastal residents from the projected path of Cyclone Sidr."

Immediately after the storm, the Government of Bangladesh collaborated with the United Nations, the National Red Crescent Society, and the International Federation of Red Cross and Red Crescent Societies (IFRC) which supplemented first responders from

the USMC and Coalition Armed Forces to conduct humanitarian aid survey team (HAST) operations to provide appropriate HADR (GOB, 2008a).

Super Cyclone Sidr was a natural disaster which had unexpected results. Due to historical data, the GOB and its emergency responders predicted and prepared for a cholera outbreak that never occurred (Paul et al., 2011). Population deaths and injuries sustained from Cyclone Sidr were higher in comparison to those who suffered illnesses in relation to the disaster. The GOB prepositioned and stockpiled basic hygiene kits to ensure rapid distribution to the affected population in order to prevent and control secondary illnesses and outbreaks (Haque et al., 2012). A summary of post-humanitarian efforts states "A major outbreak of such diseases was largely avoided because of the proper distribution of food and safe drinking water, as well as the timely implementation of health care intervention measures" (Paul et al., 2011).

An empirical study conducted to examine pattern and extent of illness post Sidr surveyed 277 community members among a total population of 1,443 in the cyclone affected areas. Of the sample population only 3.6% suffered a disaster related illness. Of those who suffered an illness, 38% suffered from a diarrheal disease/cholera. The findings indicate that the GOB planning for epidemic outbreaks of cholera and other diseases and taking appropriate prevention measures significantly reduced the incidence of disease post disaster (Paul et al., 2011).

D. HAITI EARTHQUAKE

On January 12, 2010, Haiti was devastated after a 7.0 magnitude earthquake struck the capital city. The earthquake affected 3.5 million people, killing more than 220,000, injuring another 300,000, and leaving over 1.5 million people homeless (DEC, n.d.).

Immediately post the earthquake the CDC wrote that "[a]n outbreak of cholera [was] very unlikely." This was a reasonable assessment since there was little history of cholera in the country (Fisher & Kramer, 2012). Cravioto et al. (n.d.) state:

> A review of hospital admission records along the Artibonite River from the mountains of Mirebalais to St. Marc on the coast clearly showed that a

> normal background rate of non-fatal diarrheal disease in adults and children was abruptly interrupted by the onset of a cholera outbreak. The first hospitalized cholera case in Mirebalais, in the upstream region of the Artibonite River, was on the evening of October 17th, 2010. The first hospitalized cholera cases on the coast, in the Artibonite River Delta in St. Marc and Deschapelle, were on October 20th, 2010. The outbreak was widely established in the coastal areas by October 22nd, 2010. The timeline suggests that the outbreak spread along the Artibonite River. (p. 3)

Haitian public health officials quickly identified the source of illness as cholera and announced the reemergence of cholera within the country in over 100 years (Cholera in Haiti: One year later, n.d.).

Prior to the disaster, Haiti already had inadequate public hygiene infrastructure as over 80% of the population did not have direct access to suitable water, sanitation, and hygiene (WASH) facilities (Fisher & Kramer, 2012). The earthquake destroyed the existing WASH infrastructure and allowed for cholera to exponentially spread throughout the population (Fisher & Kramer, 2012).

Post-earthquake large portions of the Haitian population were forced to live in displaced persons camps. While close contact may have contributed to the cholera spread, studies show, "most residents of the camps were actually 'largely spared from the outbreak' (Kramer, 2012) because of the clean water and medical supplies that the camps provided" (Fisher & Kramer, 2012).

Fisher and Kramer (2012) state the origins of the cholera were determined as follows:

> Researchers eventually determined that the strain of cholera responsible for the outbreak was consistent with strains found in South Asia and may have been introduced into Haiti by peacekeepers from Nepal who were part of the United Nations Stabilization Mission in Haiti. Furthermore, "patient zero" was identified as a 28-year-old Haitian who was exposed to cholera while bathing in, and drinking from, a river near the peacekeepers' camp.

As of 2015, "470,000 cases of cholera have been reported in Haiti with 6,631 attributable deaths" (Cholera in Haiti: One year later, n.d.). As of the end 2011, over

21,000 Cholera cases and 363 associated deaths have been documented in the neighboring Dominican Republic (Fisher & Kramer, 2012). The cholera outbreak in Haiti, while devastating was well documented and serves as critical lessons learned for response and preparation of future potential outbreaks (Cholera in Haiti: One year later, n.d.).

E. CHOLERA STOCKPILE

In 2011, the World Health Assembly implemented Resolution 64.15 (WHA64, R, 2011) calling for the reduction of cholera through the use of vaccines stating "where appropriate, in conjunction with other recommended prevention and control methods and not as a substitute for such methods" (ICG, 2013).

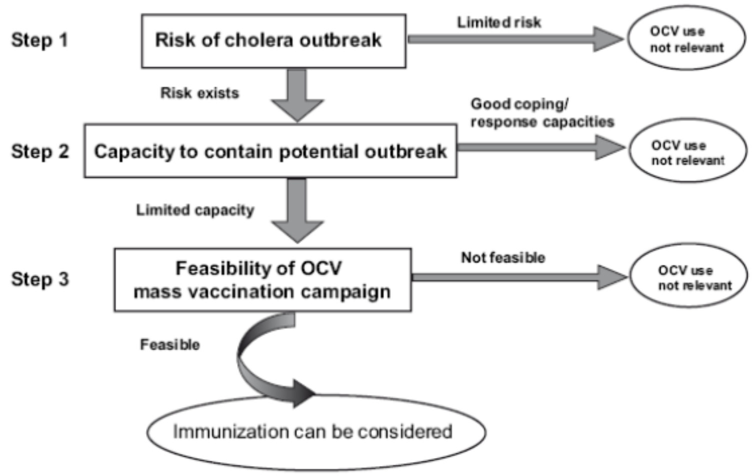
In September 2011, the World Health Organization (WHO) Secretariat organized a technical consultation which recommended the creation of an oral cholera vaccine (OCV) stockpile for outbreak control (WHO, 2012). The WHO recommended that the OCV stockpile be used preemptively vice reactively due to the short duration of many cholera outbreaks; advising that an epidemic may be over before the vaccinations can be distributed to the affected population (Maskery et al., 2013). An appropriate stockpile would alleviate any demand shortfalls that may cause political unrest and potential for ethical sensitives when choosing what portion of an at risk population to vaccinate.

Currently only two OCVs are prequalified by WHO and could be used for an immediate stockpile: Dukoral® and Shanchol™ (ICG, 2013). In terms of efficacy, "both WHO pre-qualified are oral killed whole-cell vaccines (WC) that provide sustained protection of >50% for at least two years in endemic populations induce an immune response relatively quickly (7–10 days after the 2nd dose) and have a good safety profile" (Jertborn et al., 1993, Grading Table I, n.d.). Management and distribution of both OCVs require a cold supply chain and are issued in two doses between one to six weeks apart (ICG, 2013). The current annual manufacturing capacity of Shanchol™ is only 2–2.5 million doses (Maskery et al. 2013).

The ICG has recommended three objectives for cholera epidemics: “provide appropriate treatment to people with cholera, implement interventions to improve water and sanitation, and mobilize communities” (ICG, 2013). The ICG also recommends that “pre-emptive vaccination should be considered by local health authorities to help prevent potential outbreaks or the spread of current outbreaks to new areas.” Additionally, in lieu of prolonged outbreaks of cholera affecting larger populations, reactive vaccination programs should be considered by local governments and health officials. These reactive programs should be based on historical epidemiological data in order to target correct population (ICG, 2013). As Maskery et al. (2013) note “targeted use in cholera-endemic populations outside of outbreaks should be addressed through parallel efforts to insert OCVs into national vaccination programs.”

The “3-step decision-making tool developed for crisis situations, to guide policy-makers in their decision on whether to use OCV during complex emergencies” (WHO, 2010b, p.1) is shown in Figure 5. The goal of the decision-making tool is to help determine whether a mass OCV immunization campaigns in necessary in the event of a natural disaster or other complex emergency. The WHO (2010b, p. 47) defines complex emergencies as “situations in which a large part of the population is affected, leading to potential massive population movements; the coping capacities of local and national authorities are overwhelmed by the magnitude of the man-made or natural disaster; numerous national and international actors may participate in the relief effort.”

Figure 5. Decision-making tree for OCV use in complex emergencies



Source: International Coordinating Group (ICG). (2013). Oral cholera vaccine stockpile for cholera emergency response. World Health Organization. Retrieved from http://www.who.int/cholera/vaccines/ocv_stockpile_2013/en/ p.9

The WHO has determined that the initial stockpile size consisting of Dukoral® and Shanchol™ should be 2 million doses (ICG, 2013). In the demand determination for an OCV stockpile the size of the at-risk population is not the only factor. Maskery et al (2013, p. 18) also discusses "other key factors include countries' desire to deploy these vaccines, their ability to rapidly implement cholera vaccination, the expected coverage rates, the availability of vaccine, and the availability of funding, both from donors and from countries' operational budgets for vaccination campaigns." Limitations in manufacturing, funding, and demand uncertainty will require global coordination for stockpile use "as the supply is subdivided by the demand for emergency use and the demand for preventive use in cholera-endemic countries" (Maskery et al. 2013, p. 18).

F. PAST USE OF OCV IN COMPLEX EMERGENCIES

Past data on mass OCV campaigns is demonstrated in Table 1. All data collected was associated with preemptive strategic campaigns due to displaced populations to refugee camps post natural or manmade disasters. The country of Vietnam is the most extensive user of preemptive OCV vaccination campaigns and had administered over 20 million doses to high risk populations especially following floods within the country

(Anh et al., 2011; DeRoeck & Jodar, 2004; Khiem et al., 2003). One instance of reactive vaccination campaign was in Hanoi in 2008 in which “an estimated 80% of the 370 000 persons eligible for vaccination received ≥1 dose. The vaccine was estimated to be 76% effective on the basis of a case-control study” (Anh et al., 2011). In Uganda, Darfur, and Indonesia, “cholera vaccination was found to be feasible, although logistical issues resulting from the crises (example: the destruction of roads in Aceh) and the vaccine (bulky packaging and the need to administer with a buffer) created challenges” (Maskery, 2013). Effectiveness of vaccines among vaccinated populations was not available since no cases occurred in those populations (Dorlencourt et al., 1990; WHO, 1999).

Table 1. Past use of OCV in emergency or post crisis situations

Location (Period)	Population Targeted	Strategy Type	Vaccine	Doses, No.
Vietnam (1997–present)	High-risk populations	Preemptive and reactive (eg, following floods, in areas in and surrounding cholera outbreaks, preemptively among high-risk populations)	ORC-VAX (locally produced killed WC vaccine)	>20 million
Northern Uganda (1997)	Sudanese refugees in 6 stable refugee settlements	Preemptive	Dukoral (2-dose WC/rBS)	63 220
Mayotte[a] (2000)	Local population	Preemptive (during cholera outbreak on other islands of Comoros)	Dukoral	93 000
Pohnpei, Micronesia (2000–2001)	Population in Pohnpei and surrounding islands	Reactive (in response to outbreak in Pohnpei)	Orochol (live single-dose CDV 103-HgR)	48 000
Darfur, Sudan (2004)	Internally displaced persons in 2 camps	Preemptive	Dukoral	103 000
Aceh, Indonesia (2005)	Internally displaced persons following the tsunami	Preemptive	Dukoral	137 000

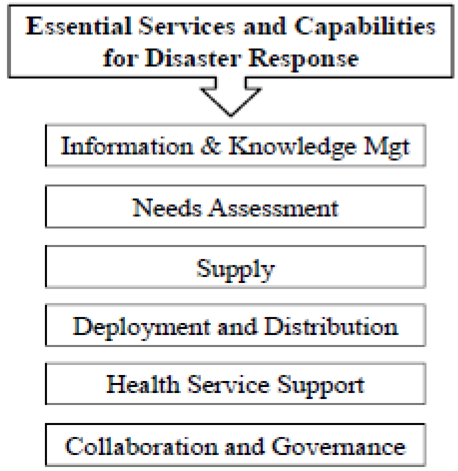
Abbreviations: rBS, recombinant cholera toxin B subunit; WC, whole cell.
[a] A French island southeast of Comoros.

Source: Maskery et al. (2013). Strategy, demand, management, and costs of an international cholera vaccine stockpile. *Journal of Infectious Diseases*, *208* (suppl 1), S15-S22

G. NEEDS ASSESSMENT

Due to the inherent nature of natural disasters the scope of demand post disaster is inherently unknown and “gives rise to a wide range of needs that may be characterized by both scale and scope” (Apte & Yoho, 2012). Apte and Yoho (2012) summarize the essentials to delivering aid to those affected by disasters in Figure 6.

Figure 6. Essential services and capabilities for disaster response



Source: Apte, A., & Yoho, K. (2012). *Capabilities and competencies in humanitarian operations*. Aquisition research paper, Naval Postgraduate School, Monterey, CA

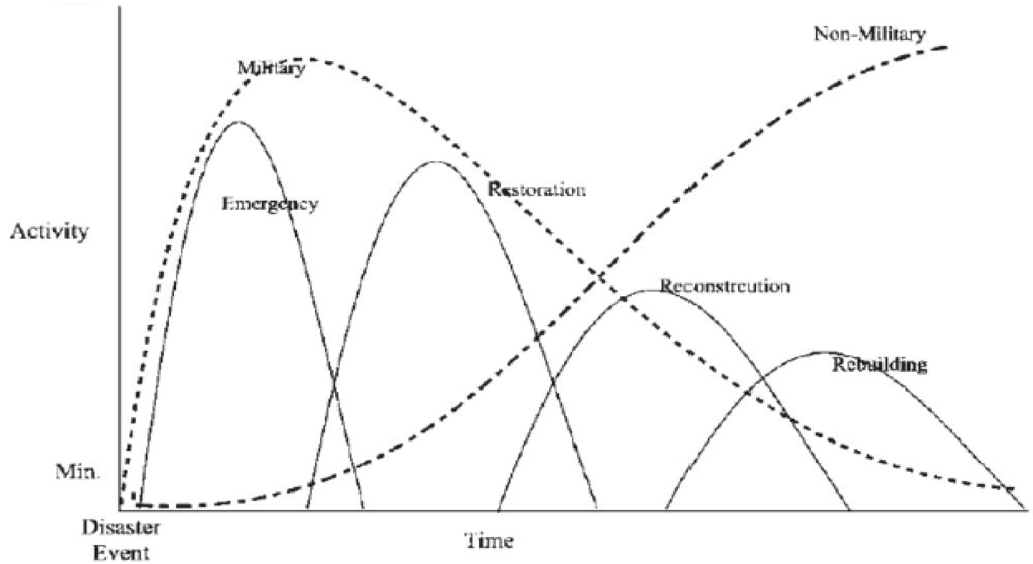
When discussing U.S. military involvement, the needs assessment is the requirements generation based on the current operational picture. Apte and Yoho (2012) note "the needs assessment is critical for determining the scale and scope of disaster aid that must be delivered to the affected area as well as for estimating the local capacity to receive, organize, distribute, and manage the aid." The needs assessment produces a statement of capabilities and associated missions in order to efficiently deliver aid to the affected population.

The needs assessment that is conducted by U.S. military responders includes use of intelligence assets, insertion of special forces as required, requirement inputs from the host nation, and use of a Humanitarian Aid Survey Team (HAST) belonging to the MEU.

The needs assessment will highlight critical demand supplies and services of the affected population and attempt to match a military capability (supply) to meet such demand. The capabilities supplied by the U.S. military are a concerted effort to decrease the "gap of pain," (Curculo, 2006), which is described as "the time period between when domestic relief efforts are exhausted and when outside relief efforts arrive" (Greenfield & Ingram, 2011, p. 3). The U.S. military will continue to be the primary supply source of

aid until NGOs are able to fully execute operations at their full capacity (Figure 7) (Pettit & Beresford, 2005).

Figure 7. Military versus non-military response during disasters over time



Source: Pettit, S. J., & Beresford, A.K. (2005). Emergency relief logistics: An evaluation of military, non-military and composite response models, *International Journal of Logistics: Research and Applications*, *8*(4):313–331.

H. MARINE CORPS CAPABILITIES AND RESPONSE

The Marine Corps is an expeditionary force that operates as a Marine Air Ground Task Force (MAGTF). Marine Corps Doctrinal Publication 1 (1997) states:

> MAGTF's are task organizations consisting of ground, aviation, combat service support, and command elements. They have no standard structure, but rather are constituted as appropriate for the specific mission. The MAGTF provides a single commander a combined arms force that can be tailored to the situation faced. (USMC, 1997)

With personnel strength of approximately 2200 Marines and Sailors, the Marine Expeditionary Unit (MEU) is the smallest and most versatile MAGTF that is consistently forward deployed, embarked on amphibious assault ships within various areas of operations. This "flexible sea-based MAGTF is capable of conducting amphibious operations to respond to crisis, conduct limited contingency operations, introduce follow-

on forces, and support designated special operation forces" and is self-sustainable for 15 days (USMC, 2013).

For the sake of this paper, the focus will be on Marine Corps Task 1.6.6.7, Conduct Humanitarian Assistance (HA) defined in Marine Corps Order 3120.9C, Policy for Marine Expeditionary Units and Marine Expeditionary Units Special Operations Capable (2009) as:

> Assistance to relieve or reduce the results of natural or man-made disasters other endemic conditions such as human pain, disease, hunger, or privation that might present a serious threat to life or that can result in great damage to or loss of property. Normally these operations are limited in scope and duration. The assistance provided is designed to supplement or complement the efforts of the host nation, civil authorities and/or agencies that may have the primary responsibility for providing humanitarian assistance. (p. 5)

Post needs assessment, the MEU is normally asked to provide basic necessities post disaster, including but not limited to clean food and water, shelter, and medical support. Within the 2200 Marines and Sailors organic to the MEU, each MEU deploys with a health services support (HSS) capability that falls under the logistics element. The health services support detachment (HSSD) consists of "an emergency physician, physician assistant, critical care nurse, medical plans officer, independent duty corpsman," and a small platoon of hospital corpsman (USMC, 2012). Additionally MEUs may deploy with industrial hygiene, entomology, and preventive medicine officers and staff, dental detachments, and a shock trauma platoon (USMC, 2012).

Post disaster it can be expected that a country's medical facilities and infrastructure will either be destroyed or immediately exceed capacity, resulting is shortage of medical supplies and medical personnel to support the affected population. The MEU, its HSSD, and even Navy personnel from the amphibious ready group (ARG) can act as a stop gap as local medical capabilities become quickly overwhelmed. In the case of secondary disasters, such as cholera, the MEU and its associated manpower can service the vehicle in which to launch a mass vaccination campaign to prevent the spread of epidemics. A mass vaccination campaign was proven feasible after the Haiti

Earthquake in 2010 when the ARG/MEU administered over 8,000 immunizations to the local population (BATARG/22d MEU, 2010).

I. CHAPTER SUMMARY

This chapter explored the classifications of natural disasters and focused on the indirect health impacts associated with disasters, namely the disease cholera. The chapter specifically traced secondary impacts of cholera through three recent natural disasters and the different disaster preparations and relief efforts to handle secondary illness. It highlighted a potential cholera stockpile and associated advantages, disadvantages, and use decision making processes. Finally, the chapter discussed a needs assessment and United States Marine Corps capabilities that could be utilized to commence a mass vaccination campaign against secondary illnesses.

III. OPTIMIZATION AND SIMULATION

A. BACKGROUND

The primary scope of this project is to determine the optimal number of vaccines to store in the national stockpile in order to ensure effective distribution to an affected population during complex disasters.

1. Cholera Vaccine Inventory Model

We use mathematical models as analytical tools such as inventory models with uncertain demand of perishable items (newsvendor model) and simulation models. As previously mentioned, the newsvendor model is an optimization tool that is useful for perishable items with uncertain demand such as vaccines. It allows us to find an optimized quantity of a perishable good that maximizes profit under probabilistic demand. Additionally, our model, the Cholera Vaccine Inventory Model (CVIM), takes into account the expiration date, cost of over and under stocking, and any salvage value the vaccine may have after expiration. The CVIM optimizes the number of vaccines to manufacture and stockpile in order to reduce overall costs or net penalties. However, there are many other contributing factors that affect what the newsvendor model predicts as the optimal quantity.

2. Natural Disaster and Cholera Simulation Model

In order to determine the factors that influence the CVIM and more accurately calculate optimal quantities, we use a second analytical model. The Natural Disaster and Cholera Simulation Model (NDCSM), our simulation model, incorporates proportions of complex natural disasters occurring in specified regions (continents), the anticipated number of cholera cases, and case fatality rates associated with the disease. A simulation model is a tool used to replicate real world scenarios to gather results of 'what if' scenarios. Both these models, CVIM and NDCSM, help us analyze appropriate contributing factors to ensure accuracy of planning for a national cholera stockpile based on associated costs and probability of outbreak occurrence.

B. NATURAL DISASTER AND CHOLERA SIMULATION MODEL

1. Model Description

The NDCSM is an analytical model that seeks to forecast the number of cholera causing natural disasters that will occur in the defined regions of the world in any given year. This information is then used to predict the number of cholera cases that will result in such a disaster to assist emergency planners in preparing for a secondary disaster.

The simulation model incorporates several factors in relation to natural disasters and cholera. We developed this model based on the following information:

1. Types of disasters that cause a secondary cholera outbreak.
2. Probability of cholera causing natural disaster occurring in any given region in a given year.
3. Distribution of cholera cases in a given region given there was a cholera causing natural disaster.
4. Probability of death given the cholera vaccination was given.
5. Probability of death given the vaccination was not given.

During our research, very little of this data could be found. In fact, the only readily available data was from the World Health Organization Cholera Report, namely the number of cholera cases in each region per year, the number of cholera deaths in a given region per year, and their case fatality rate (CFR), or the rate of death if a vaccination is not given (World Health Organization, 2015).

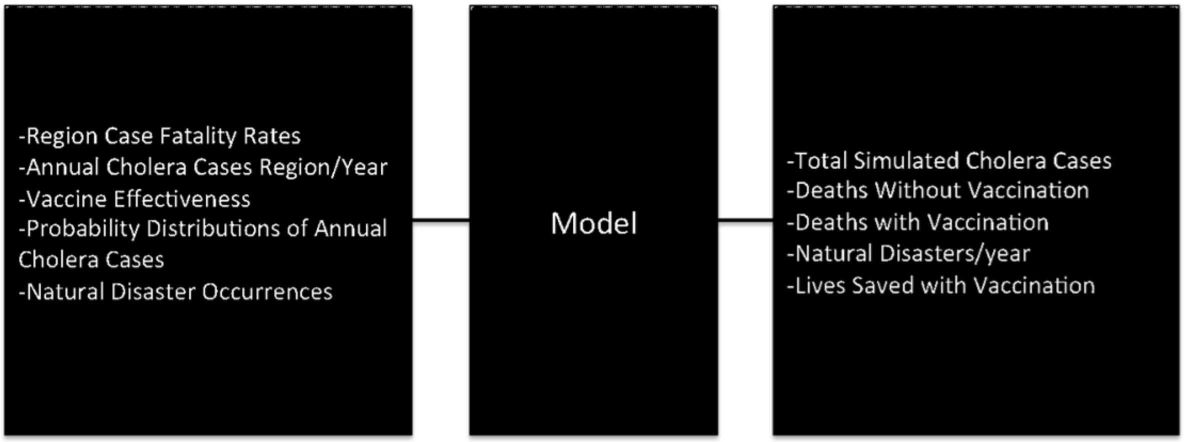
2. Data and Methodology

a. Planning Horizon and Other General Data

The NDCSM projects annual rates of cholera causing natural disasters, cholera cases caused by the natural disaster, and fatality rates based on whether or not a vaccination is given based on historical evidence. A major assumption in this model is that if a cholera causing natural disaster occurs in a region then a secondary disaster of cholera will follow.

The NDCSM requires certain inputs in order to provide the outputs described. The inputs needed to obtain the required outputs are shown in Figure 8.

Figure 8. Inputs/outputs of the natural disaster and cholera simulation model



b. Selection of Natural Disasters

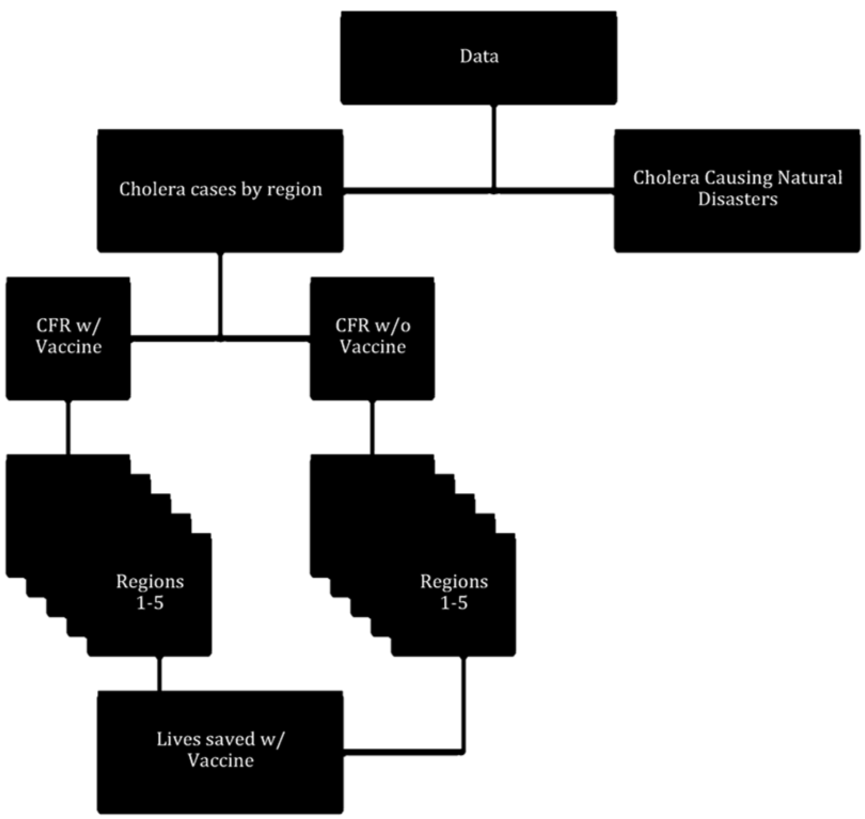
The research conducted for this project focuses solely on those natural disasters that can result in a secondary natural disaster of cholera infection. According to the Center for Disease Control (CDC, 2014), cholera is contracted "by drinking water or eating food contaminated with the cholera bacterium. In an epidemic, the source of the contamination is usually the feces of an infected person that contaminates water and/or food." This statement implies that cholera causing natural disasters must enable the mixing of feces and the water/food supply of a community or nation. We, therefore, focus further on the list of natural disasters in which this is probable such as: tropical cyclones, ground movement, floods, tsunamis, landslides, and tropical storms.

c. Data Collection

Data was collected from the Emergency Events Database (EM-DAT). EM-DAT permits the search for natural disasters by category, type, region, timeframe, death rate, damage estimations, and other factors. Data was sorted by natural disaster type between the years 1915 and 2015 in order to build a more robust data set for the NDCSM. We eliminated disasters that would not produce a high probability of a cholera outbreak as a

secondary effect (i.e., fire, famine). Disasters with the likelihood of a secondary cholera outbreak were then sorted out by type and included: tropical cyclones, ground movement, floods, tsunamis, landslides, and tropical storms. These disasters were then sorted by region and year of occurrence. We then aggregated the data by region and occurrence to determine the percentage of disasters that occurred in each region in a given year. These numbers were then averaged over the last 100 years, 40 years, and 20 years. The three time periods mentioned were chosen due to the significant increase in natural disasters over the past 100 years and to dispel any bias from lack of reporting in earlier years, changes in weather patterns, or significant increases in population near coastal areas. While it was observed that the difference in probabilities was small, all three were run to determine the impact of the estimates on the total estimated disasters, cholera cases, and deaths associated with cholera in any given year. The flow of data necessary to implement the NDCSM is shown in Figure 9.

Figure 9. Model data flow



d. Cholera Cases and Cholera causing Natural Disasters

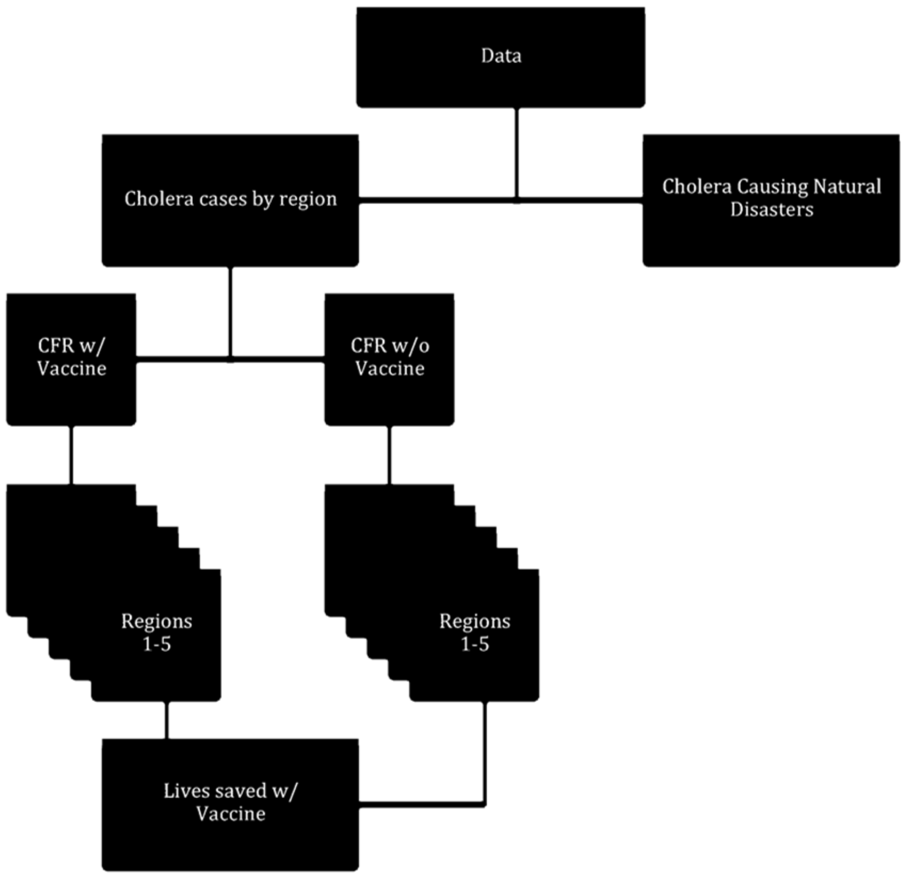
The 2014 World Health Organization Cholera Report provided the information required to find a probability distribution of cholera cases in the different regions. We took the last 20 years (1993–2013) of report data including number of cases per region, deaths associated with cholera, and the CFR. Some reports did not provide the CFR, so we divide the number of deaths by the number of cases to get this information. We fit the collected cholera data in each region in a probability distribution using the software Crystal Ball (Oracle based). From this data, we were able to run a simulation for each region 500,000 times using the distribution given in order to accurately predict the number of cholera cases per year per region. The simulation described above only gives us the predicted cholera cases for each region based on the distributions obtained from Crystal Ball and historical data. It is necessary to narrow down the scope of these cases to those associated only with cholera causing natural disasters as defined earlier in this paper. To do this, we incorporate the probability of occurrence of these types of disasters. For accuracy, we use the Crystal Ball random number feature together with the probability of disasters from historical data. The cases in each region are only counted if there is a natural disaster in that region. This simulation gives us the actual number of cholera causing natural disasters that occur in each region. Our assumption is that if a natural disaster occurs in a region, it will result in a cholera outbreak. This allows a conservative result from the simulation.

e. Case Fatality Rate

The World Health Organization Cholera Report provides the CFR for each region by year with some exceptions. This rate was associated with deaths from cholera without vaccinations. In order to determine the impacts of the vaccination and ultimately, how many of the vaccinations should be stocked, we determine the number of deaths if the affected population is vaccinated or not. In order to simulate this data, the CFR for each region is averaged over the 20-year period. This percentage is then used to determine the CFR of the simulated number of cases determined in the previous section. We multiply

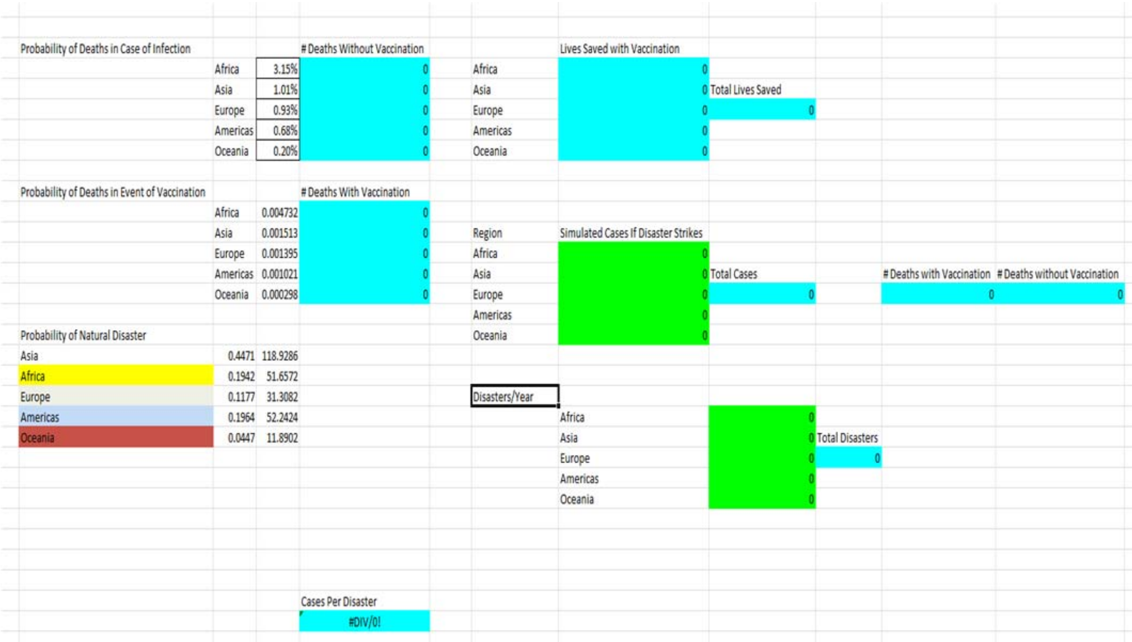
this rate by the effectiveness of cholera vaccinations (85%) to determine the case fatality rate of epidemic cholera given that the vaccine was available and given to the affected population. The flow of the NDCSM is shown in Figure 10.

Figure 10. Qualitative design of natural disaster and cholera simulation model



Once all data above is collected, it is placed into the NDSCM. The design of the model within Crystal Ball is shown in Figure 11. The cells highlighted in blue are designated as forecast cells. For example, the cell E5 is the forecast for the number of deaths in Africa if there is no vaccination. This number is derived by multiplying the CFR for by the simulated number of cholera cases for Africa. By making this cell a forecast cell, Crystal Ball tracks the results and provides graphs and statistics for each cell.

Figure 11. Screen shot from Crystal Ball of natural disaster and cholera simulation model



f. Results

(1) Total Disasters

Upon collecting and analyzing the data and running the simulation model we find a noticeable upward trend in the number of natural disasters since 1915. This trend is due to several factors including an increase in population near coastal areas, better disaster reporting mechanisms, and increased frequency of natural disasters. The significant delta in the total number of disasters between 100-year and 20-year historical data is shown in Figures 12 and 13.

Figure 12. 100-Year natural disaster frequency data

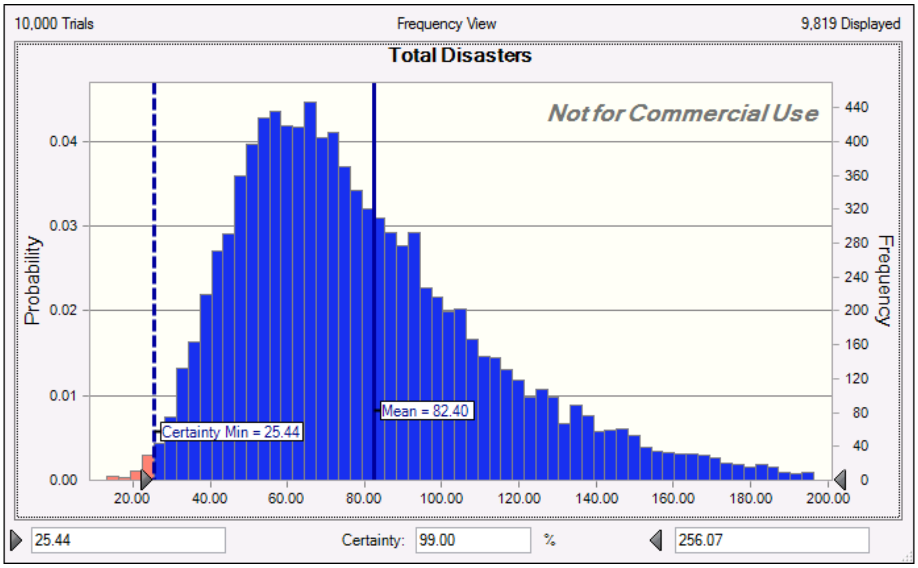
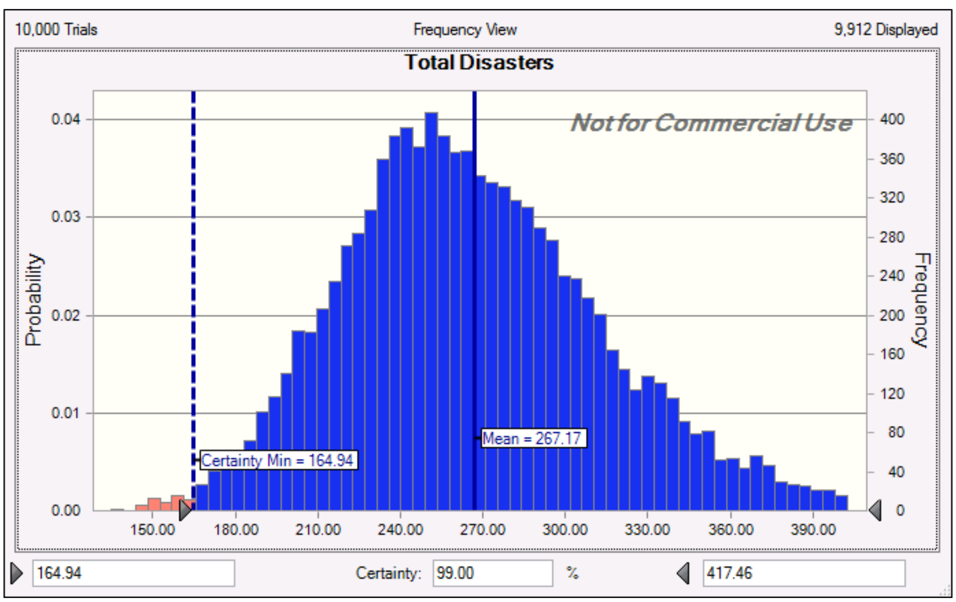


Figure 13. 20-Year natural disaster frequency data



After running the model with 20, 40, and 100-year data, and noticing the significant upward trend between the three data sets, we use 20-year dataset. While the number of disasters is on a slight down trend over the past couple of years, we are confident that the 20-year data gives the best representation over time.

(2) Total Cholera Cases

The decision to use 20-year disaster data resulted in using 20-year data for the number of reported cholera cases in each region. Since the number of cholera cases that occur on an annual basis is random, it was necessary to fit the 20-year data to a probability distribution. Each region's data was fitted to its own distribution and can be found in Table 2.

Table 2. Regions and assigned probability distributions

Region	**Distribution**
Africa	Triangular
Asia	LogNormal
Europe	Pareto
Americas	Gamma
Oceania	LogNormal

After 10,000 simulations, the mean came to 260,527 cases of cholera in any given year, with the 95th percentile at 521,010 cases. While the mean is low considering the number of natural disasters that occur, the standard deviation of the mean is extremely high at 3.1 million cases. The variability in the simulation demonstrates the stochastic nature of the both natural disasters and the appearance of cholera. As discussed, the mean for the 10,000 trials is 260,527 cases. Even at the 95th percentile, that number is only 521,010 cases. However, between the 95th and 100th percentile that number increases to over 315 million cases. This amount of variability makes it very difficult to predict what will actually happen so we use the Bootstrap Tool to increase the accuracy of the simulation. The results of the NDCSM in regard to total cholera cases and the impact of the major outliers on the mean can be seen in Figures 14, 15, and 16

Figure 14. Total cholera case mean distribution with 95th percentile in 10,000 trial simulation

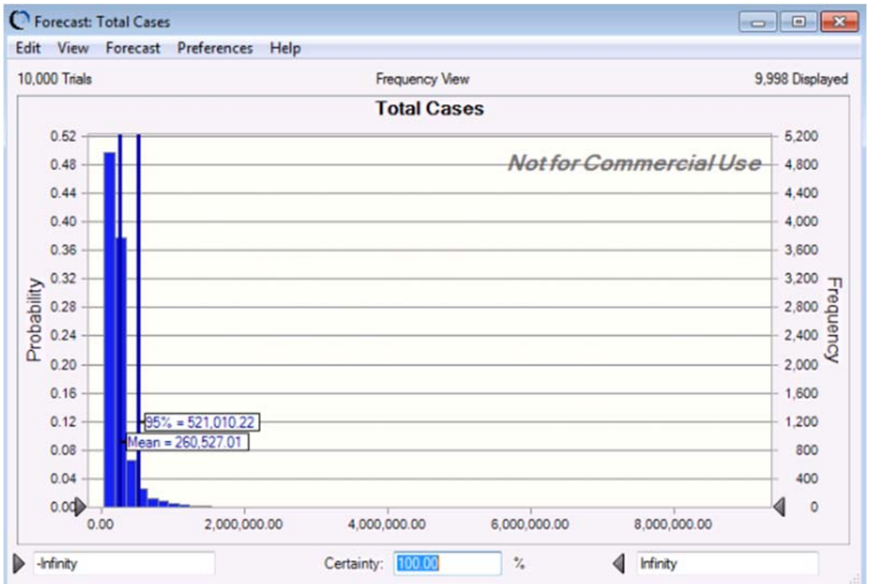
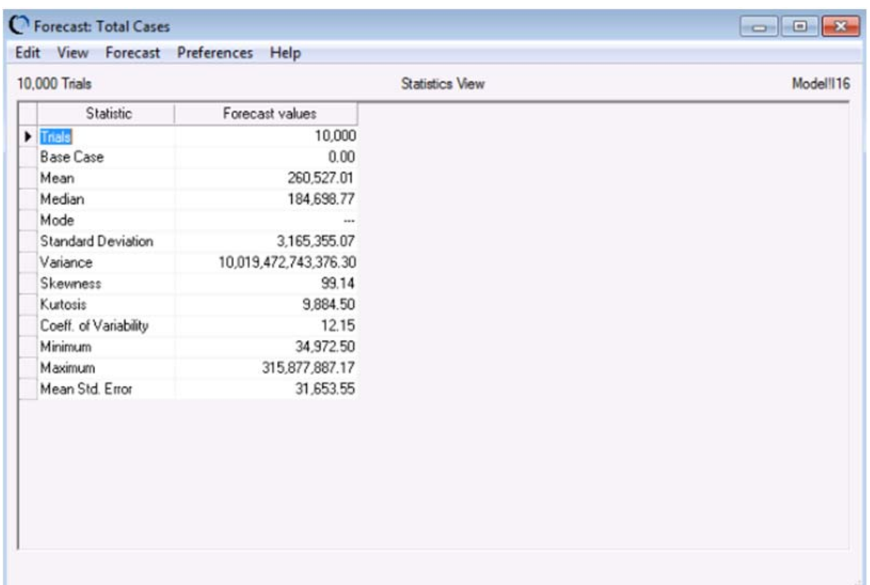
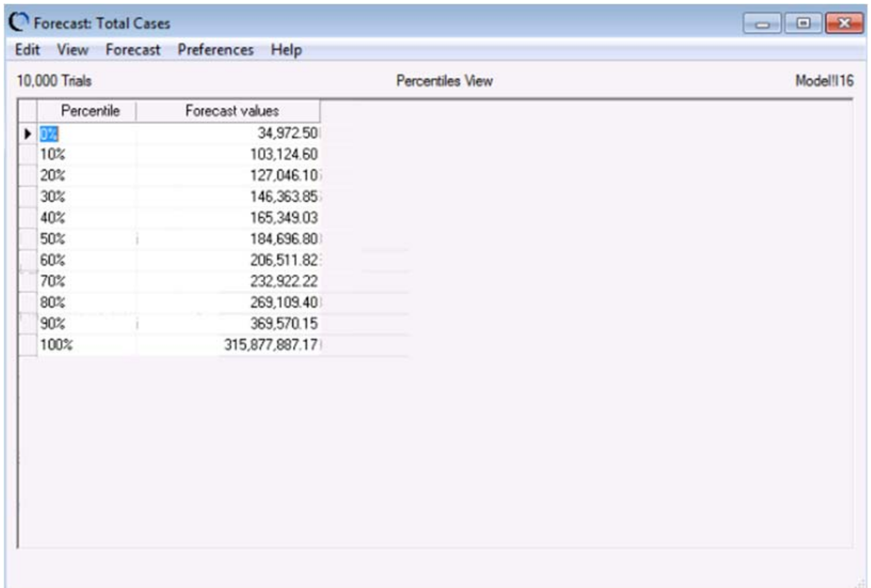


Figure 15. Total cholera case mean distribution statistics in 10,000 trial simulation



Statistic	Forecast values
Trials	10,000
Base Case	0.00
Mean	260,527.01
Median	184,698.77
Mode	---
Standard Deviation	3,165,355.07
Variance	10,019,472,743,376.30
Skewness	99.14
Kurtosis	9,884.50
Coeff. of Variability	12.15
Minimum	34,972.50
Maximum	315,877,887.17
Mean Std. Error	31,653.55

Figure 16. Total cholera case mean distribution percentiles in 10,000 trial simulations



Percentile	Forecast values
0%	34,972.50
10%	103,124.60
20%	127,046.10
30%	146,363.85
40%	165,349.03
50%	184,696.80
60%	206,511.82
70%	232,922.22
80%	269,109.40
90%	369,570.15
100%	315,877,887.17

Bootstrapping is a tool within Crystal Ball that estimates the accuracy of statistics (Oracle Corporation, 2008, p. 1). It “works by randomly sampling the forecast data and then creating distributions of the statistics from each sampling” (Oracle Corporation, 2008, p. 1). We then use these distributions to execute the simulation for 200 trials 1000 times each in order to get a good sampling from the simulation. The mean of all of the means as well as the statistics in the bootstrap simulation can be seen in Figures 17 and 18. Analysis of the percentiles in Figure 19 shows the effect of outliers with the 95th percentile at 415,857 and the 100th percentile being 6,443,389. The results show the mean total cases of cholera remain about the same showing 316,868, a difference of approximately 56,000 cases from the original simulation. However, the standard deviation of the mean of means dropped by over 2.6 million.

Figure 17. Total cholera case mean distribution with 95th percentile in bootstrap simulation

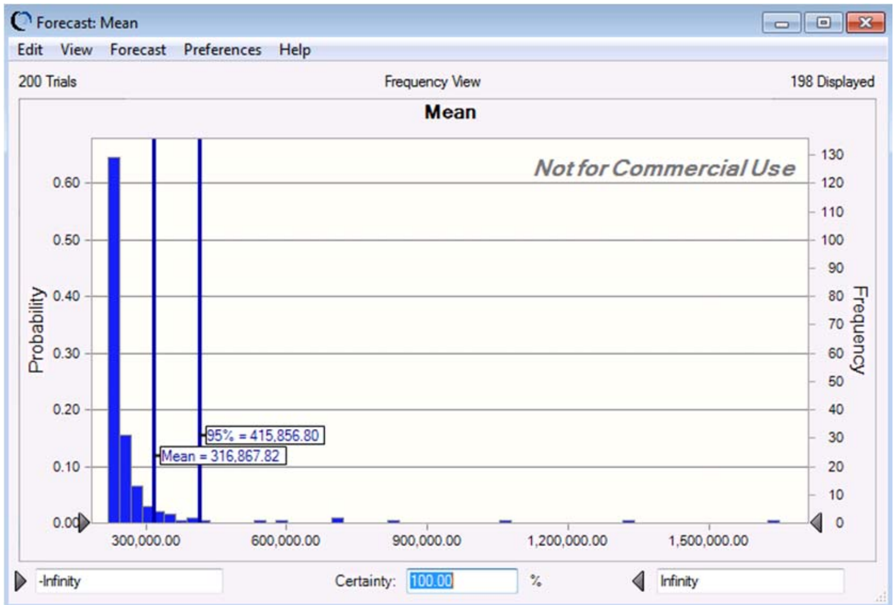


Figure 18. Total cholera case mean distribution statistics in bootstrap simulation

Statistic	Forecast values
Trials	200
Base Case	---
Mean	316,867.82
Median	237,655.46
Mode	---
Standard Deviation	483,807.83
Variance	234,070,013,426.07
Skewness	10.67
Kurtosis	130.30
Coeff. of Variability	1.53
Minimum	221,124.47
Maximum	6,442,389.27
Mean Std. Error	34,210.38

Figure 19. Total cholera case mean distribution percentiles in bootstrap simulation

200 Trials

Percentile	Forecast values
0%	221,124.47
10%	226,628.47
20%	229,307.47
30%	231,449.18
40%	234,704.17
50%	237,626.08
60%	240,668.54
70%	249,050.96
80%	266,422.01
90%	318,120.98
100%	6,442,389.27

Table 3. Comparative statistics between 10,000 trial simulation and bootstrap

	Simulation	Bootstrap
Mean	260,527 cases	316,868 cases
Standard Deviation	3.1 million cases	483,808 cases
95% certainty	521,101 cases	415,858 cases

Comparative statistics between the simulation and the bootstrap are shown in Table 3. This data shows that while the overall mean has increased by over 50,000 cases, the standard deviation or variability in the data has decreased significantly. While the standard deviation is still high compared to the mean, it gives a better analysis of the situation than simulation alone.

C. CHOLERA VACCINE INVENTORY MODEL

1. Model Description

The CVIM, or newsvendor model, is an analytical optimization model that seeks to estimate the optimal number of cholera vaccines to store in order to reduce penalties or costs. This information can assist planners in production, necessary storage space, determination of national stockpile, and resource needs when preparing for secondary disasters. The newsvendor optimization model incorporates several factors in relation to optimal stocking of cholera vaccines. The information that is necessary to conduct the newsvendor model includes the following:

1. Random demand of cholera vaccines
2. Shelf-life of vaccines
3. Distribution of cholera cases in a given region given there was a cholera causing natural disaster
4. Overstock and under stock penalties associated with the cholera vaccine
5. Salvage value of the vaccine, if any

We were able to find most of this information during our research. The information we were unable to find, we made educated assumptions based on known military costs associated with transportation and refrigerated storage of the vaccine in the disaster area.

2. Data and Methodology

a. Planning Horizon and Other General Data

The newsvendor model projects the optimal number of annual vaccinations required to treat Cholera cases resulting from natural disasters.

b. Data Collection

(1) Overstocking Penalty

In order to determine the penalty associated with having too much of the vaccine, it was necessary to determine the costs associated with making, storing, and transporting the vaccinations required for each affected individual. According to Schaetti et al. (2012),

the cost to produce each dose of OCV is $10.00 and each person requires two doses. Schaetti et al. (2012) also describes the ancillary costs associated with a mass vaccination campaign in Zanzibar, Africa. The details each cost is shown in Figure 20.

Figure 20. Historical costs of mass vaccination implementation

	Total[a]	Mean[b]	%
Vaccine (purchase price USD 10 per course)	**510,000**	**21**	**68**
Delivery[c]	**240,000**	**9.7**	**32**
Vaccine transport, storage, water and cups	45,000	1.8	6.0
International consultants	110,000	4.4	14
Training	9,500	0.38	1.3
Implementation	78,000	3.2	10
Total costs	**760,000**	**30**	**100**

[a]Total costs (2009 USD) to vaccinate a target population of 49,980 people;
[b]Mean costs (2009 USD) per fully immunized individual based on actual coverage (50%);
[c]Based on actual expenditure or planned budget data from 2009 mass vaccination campaign, see supporting information (Table S2) for more details.
doi:10.1371/journal.pntd.0001844.t005

Source: Schaetti, C., Weiss, M. G., Ali, S. M., Chaignat, C.-L., Khatib, A. H., Reyburn, R., Duintjer Tebbens, R. J., & Hutubessy, R. (2012). *Costs of illness due to cholera, costs of immunization and effectiveness of an oral cholera mass vaccination campaign in Zanzibar*. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3464297/

Our original calculations for transportation were half the amount shown in the table above. For the purpose of military distributed vaccination campaigns, we first took known operating costs of a United States Air Force (USAF) C-17 transport aircraft of just over $23,000 per hour with the longest trip taking approximately five hours. This estimates the cost of delivery at approximately $115,000. Since Figure 20 is based on actual data and is higher; we will use it as a more conservative estimate relating to transportation, internal delivery and implementation of the vaccine delivery.

(2) Under stocking Penalty

In order to determine the cost associated for not having a vaccine we determine the value of statistical life (VSL). Since cholera is deadly, the cost of not having the vaccine is the loss of life associated with the disease. How does one put a price tag on a human life? We use the data from health and life insurance companies. The “international standard most private and government-run health insurance plans worldwide use to determine whether to cover a new medical procedure. More simply, insurance companies calculate that to make a treatment worth its cost, it must guarantee one year of ‘quality life’ for $50,000 or less” (Kinsbury, 2008). Since this is the international standard, we use the cost of human life for not having the vaccine in stock to be $50,000 per person.

3. Results

After running the CVIM, the resulting optimized inventory level was 3,205,536 vaccines. This number is derived from 200 years of demand based on the LogNormal distribution and the over stocking and under stocking penalty. The high under stocking penalty results in the optimization model ensuring that all demand is met in each of the 200 scenarios. The optimal inventory derived from the CVIM and the visual graph associated with the numbers is shown in Figures 21 and 22. As the number of vaccines increase in the stockpile, the average net penalty continues to decline until it reaches 3,205,536. Once it goes over this optimal number, the average net penalty begins to increase slightly. This increase is due to the cost of over stocking described in the previous section.

Figure 21. Screen shot from Crystal Ball of cholera vaccine inventory model

Cholera Vaccination Model

		today (t)	182.00
Received from other model average over 10000 simulations		Stock expiration (T)	365.00
Expected demand	316868	understocking penalty(UC)	50000.00
Standard deviation	483808	overstocking penalty(OC)	20.80
Random no. seed	123	Salvage value (V)	0.00
Quantity To Stock (Q)	3205536		
	0.99500		
		Average net penalty	59426988.72

Vaccines	Ave. Net Penalty
	59,426,988.72
500,000	5,361,284,554.96
700,000	4,159,560,368.47
1,000,000	3,041,723,613.26
2,000,000	1,076,962,569.81
3,205,536	59,426,992.00
5,000,000	96,751,843.20
7,000,000	138,351,843.20
10,000,000	200,751,843.20

Year	Random Demand	Excess Supply	Shortage	Used	Penalty understock	Penalty overstock	Salvage Value	Net Penalties
	D	Q - D	D - Q	If Q>=D then D If Q<=D then Q	D-Q	Q-D	(Q-D)*(T-t)/T*V	If Q>=D then (Q-D)*OC If Q<=D then Q*UC
1	9953.379782	3195582	0	9953.38	0.00	66468115.21	0.00	66468115.2
2	632764.3247	2572772	0	632764.32	0.00	53513647.56	0.00	53513647.6
3	84191.36977	3121344	0	84191.37	0.00	64923965.02	0.00	64923965
4	48437.51959	3157098	0	48437.52	0.00	65667645.1	0.00	65667645.1
5	145034.8207	3060501	0	145034.82	0.00	63658421.24	0.00	63658421.2
6	65444.47303	3140091	0	65444.47	0.00	65313900.47	0.00	65313900.5
7	321520.0061	2884016	0	321520.01	0.00	59987529.38	0.00	59987529.4
8	564007.1105	2641529	0	564007.11	0.00	54943797.61	0.00	54943797.6
9	56433.35712	3149102	0	56433.36	0.00	65501331.68	0.00	65501331.7
10	222998.1966	2982538	0	222998.20	0.00	62036783.02	0.00	62036783
11	280521.3861	2925014	0	280521.39	0.00	60840300.68	0.00	60840300.7
12	547346.5577	2658189	0	547346.56	0.00	55290337.11	0.00	55290337.1
13	274609.3265	2930927	0	274609.33	0.00	60963271.52	0.00	60963271.5
14	375984.4681	2829551	0	375984.47	0.00	58854668.58	0.00	58854668.6
15	103401.929	3102134	0	103401.93	0.00	64524385.39	0.00	64524385.4
16	340247.1201	2865289	0	340247.12	0.00	59598005.41	0.00	59598005.4
17	374619.8489	2830916	0	374619.85	0.00	58883052.65	0.00	58883052.7
18	212726.209	2992810	0	212726.21	0.00	62250440.37	0.00	62250440.4

Figure 22. Average net penalty associated with given number of cholera vaccinations

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IV. CONCLUSION AND RECOMMENDATIONS

This study concludes that with the increasing frequency of natural disasters, outbreaks of secondary epidemics such as cholera are extremely likely. In the most recent case of the 2010 Haitian earthquake, cholera affected more people than were killed in the earthquake itself. If the United States government and military are to continue to participate in humanitarian aid and disaster relief operations across the globe, proper planning and prepositioning of assets or an increase in national stockpile of OCV needs to be addressed. Epidemic prevention is far easier than fighting an epidemic that is already spreading through an affected population. This study also recognizes the cost of such a stockpile has its limitations, but recognizes the number of lives saved through the use of a stockpile outweighs associated inventory and supply chain costs.

In consideration of the findings of this study, further analysis in the following areas is recommended.

- Cost/benefit of national stockpile utilizing alternate variables in the cholera vaccination inventory model including VSL for developed countries, civilian versus military assets for logistics distribution, and value of additional lives saved when donating about to expire vaccines to countries with endemic cholera.
- Effects of utilizing different distributions in the natural disaster and cholera simulation model.
- Distribution and causes of natural disasters over time.
- Logistics for most effective methods of distribution via military means (prepositioning, transportation, and last tactical mile).

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